



Exergy as a global energy sustainability indicator. A review of the state of the art



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ABSTRACT

This paper looks at the suitability of using exergy as an indicator for energy sustainability studies, by reviewing the relevant literature and describing and assessing the different uses that have been proposed for it as a global energy sustainability indicator.

Exergy is a thermodynamic property that links the first and the second thermodynamic principles as well as connects a system under study with the environment where it belongs. Since the first principle of thermodynamics measures quantity of energy and the second measures irreversibilities, i.e. *quality* of energy, having a single thermodynamic indicator which is able to deal with both issues at the same time means a great advance in energy sustainability studies.

Our review shows that using exergy for weak sustainability studies presents some problems, but still offers a worthy contribution to this field, more valuable than pure economic analyses. Strong sustainability assessments featuring exergy show more drawbacks and complications, but can also play a key role in a sustainability framework designed in order to obtain sustainable policies which are able to maintain homeostatic relations between the system under study and its environment, thus complementing traditional economic approaches which are mainly focused on the economic and social poles of sustainability.

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1. Introduction

“A temptation when writing on ‘defining sustainability’ is to try to distill, from the myriad debates, a single definition which commands the widest possible academic consent. However, several years spent in fitful pursuit of this goal have finally persuaded me that it is an alchemist’s dream, no more likely to be found than an elixir to prolong life indefinitely” [1].

This quotation rescued from Pezzey’s great work on sustainability is meant to be the backdrop of this research. Sustainability is a complex issue, and it seems that no simple approach will be found which is able to deal with its total complexity. On the other hand, sustainability is a privileged topic in the agenda of global concerns in our world. Institutions and governments all over the world are facing this issue at different levels, requiring ways and tools to make the complex concept operational and measurable. There can be no doubt therefore about the importance and necessity to inquire deeper into this topic in order to offer some hints which might help to advance toward *real* sustainability.

Achieving sustainability presents many challenges, in many fields. Of those, the energy sector is probably one of the most relevant: its large economic, social, environmental or technological implications, as well as the long time periods associated with it, require a careful look at the ways in which to assess the sustainability of this sector in a broader picture. This research is focused on this field, the role of energy in sustainability and the search for suitable energy sustainability indicators. In particular, a first insight into the literature brought us to a vast area of thermodynamic contributions to sustainability studies. Among all of them, a key concept emerged: *Exergy*.

Exergy is a thermodynamic variable which has been profusely used in the last decades, on the one hand as a key tool in the efficiency improvement of thermal processes, and, on the other hand, as a holistic approach to global sustainable studies. Many contributions have been offered so far, and a large controversy exists regarding the real advantages that exergy can offer to global sustainability studies. Given the relevance of the topic, and the need to devise and use operational indicators for the assessment of energy sustainability, the review of the current literature related to this concept, and the distillation of the advantages and disadvantages of using exergy as an indicator for energy sustainability, thus helping to clarify this tangled issue, is in our opinion a much welcome addition to the literature, and the objective of this paper.

We start in Section 2 by reviewing briefly the definitions, indicators and problems of current models of sustainability in general and of energy sustainability in particular. Section 3 then addresses in depth the concept of exergy, and Section 4 reviews its applications to the assessment of sustainability. Section 5 discusses the different approaches and advances a consensus position. Section 6 presents the conclusions extracted from the review.

2. Energy sustainability

We start by giving a brief introduction to the general concept of sustainability, to set up the framework against which to analyse the usefulness of the concept of exergy.

“Development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [2].

This definition of sustainability stated by the World Commission on Environment and Development in its Brundtland report of 1987 has become the classical definition for this complex concept, but it is not the only one. Among many subsequent ones, the sustainable development triangle proposed by Munasinghe at the 1992 Earth Summit in Rio de Janeiro, Brazil is another widely accepted definition. It encompasses three major perspectives: economic, social, and environmental. Each viewpoint corresponds to a domain that has its own distinct driving forces and objectives. However, although each viewpoint focuses on a certain area, they are closely related. Economic, social and environmental approaches to sustainability are complementary contributions which need each other in order to offer a complete insight. In fact, energy, which is the central topic of our research, embraces the three poles. Thus, talking about energy sustainability is not different from talking about economic, social and environmental sustainability, since all of these approaches are strongly interlinked.

Although separating sustainability in these three main topics meant an important step toward making the concept operational, it also brought some drawbacks, given that separating a problem into different parts sometimes implies an important loss of crucial information and a lack of global perspective. Hence, some alternatives to Munasinghe’s triangle were proposed. One of the most interesting ones is the model of the Russian Doll proposed by Levett [3].

As many authors highlight [4,5], finding a suitable definition for sustainability is not the same as achieving it. Yet, in any case, obtaining a way to accurately measure sustainability will always be required in order to propose the necessary reforms. This is a difficult task in which two antagonistic approaches have been competing for decades.

2.1. Strong versus weak sustainability

We cannot talk about sustainability without mentioning the classical disputation between Georgescu-Roegen [6] and Solow [7]. Two antagonistic models of the production process are embedded within this debate: the Neoclassical (Solow) and the Fund-Flow model (Georgescu-Roegen). The former constitutes the foundation for the *weak sustainability* paradigm, while the latter supports the *strong sustainability* one.

A key concept that differentiates both approaches is the *natural capital*, that is, the environment. According to Hartwick [8] and Neumayer [9], weak sustainability is rooted in the fact that natural capital is similar to produced capital and can easily be substituted for it. In turn, the strong sustainability paradigm argues that natural capital is to a greater or lesser extent non-substitutable.

Since strong sustainability is a more diffuse paradigm than weak sustainability, a number of rules have been suggested that seek to operationalize it. Neumayer [9] identifies two main schools

of thought. One requires that the value of natural capital be preserved assuming, in principle, unlimited substitutability among different forms of natural capital. The second school requires that a subset of total natural capital is preserved in physical terms so that its functions remain intact. This is the so-called *critical natural capital* (CNC).

However, other authors such as Hinterberger [10], in their conceptualization of strong sustainability, highlight the problematic use of natural capital. As he emphasizes, this notion is somewhat dangerous since an essential feature of capital is that it is reproducible by human action, which is not the case for the environment. Furthermore, this term carries the implicit assumption that the environment can be substituted by other forms of capital. These authors do not deny some analogies between capital and nature but just propose to be cautious establishing an exact comparison.

The strong and weak sustainability debate extends its influence until nowadays. Although many interpretations of this discussion have been offered, we focus mainly on Ayres [11] and Daly's [12] contributions which are found on the thermodynamic roots of sustainability. In summary, these authors defend that "while there is plenty of room for substitution and some possibility of major breakthroughs, the pessimists (strong sustainability) appear to be closer to the truth than the optimists who believe in more or less unlimited substitution possibilities".

Nevertheless, a blind adoption of a strong sustainability criterion does not seem to be the right solution for the problem we are dealing with. After defining these two extreme options: weak and strong sustainability, choosing some kind of middle way between both seems to be the most coherent election. Some degree of substitutability should be set, and according to it, some sustainable policies could be recommended. However, regardless of the level of substitutability chosen, as mentioned above, sustainability measures are needed in order to define and to evaluate sustainability goals. These measures are traditionally called *indicators*, being exergy one of them.

2.2. Sustainability indicators and models

As mentioned before, this paper will look at the usefulness of exergy as an energy indicator for sustainability studies. But as a first step, it seems to be relevant to give a brief insight into the global problems inherent to obtaining accurate sustainability indicators.

Sustainability indicators are meant to offer reliable information about the level of sustainability of an economy, a country, a society, a utility, or any system under study. Many contributions have been made regarding this topic, many of them promoted by public administrations that needed to define and to quantify the sustainability goals achieved in the application of different policies and regulations. Thus, many public institutions, like the Commission on Sustainable Development (CSD) of the United Nations [13,14], started to work on this area. Boulanger's review [15] on this topic is highly recommended.

Dozens of indicators and sets of indicators have been proposed regarding each of Munasinghe's poles of sustainability from the very beginning of the concerns about this topic. It is noteworthy that most of them are directly or indirectly related to energy issues. In fact, in order to complement the effort of the CSD and to provide a higher resolution of energy development, in 1999 a coordinated project led by the International Energy Agency (IEA) on Indicators for Sustainable Energy Development (ISED) was launched [14].

Indicators usually measure a definite aspect of the global sustainability landscape. Hence, a problem arises when some aggregation of them is needed in order to offer a global

perspective. A vast literature can be found regarding this issue. Some aggregated indexes of sustainability have been obtained, although their accuracy as social, economic or environmental sustainable indexes is not so clear [16]. The aggregation of indicators is a very complicated issue but of crucial importance in decision-making. One of the most important problems that all of these proposals have to face is the mathematical consistency. Ebert's contributions regarding this area are relevant [17]. He concludes that certain indexes are not to be used as aggregated sustainability indicators because of the variety of their disaggregated scales.

One central problem in the aggregation of indicators is their valuation. Aggregation requires dealing with similar, or at least comparable units. How could we ensure that indicators are truly measuring what they actually try to? Moreover, since sustainability is a concept so intimately linked to human welfare: is it possible to objectively measure these subjective concepts? Traditionally, pure economic approaches have been used to deal with this issue, but many problems regarding its inherent reductionism have been highlighted.

2.3. Problems of valuation

Many approaches to sustainability, although accepting Munasinghe's division of sustainability in three poles (economic, social and environmental), usually tend to reduce all kinds of indicators, whatever type they belong to, to their equivalent monetary values. This is a controversial issue where, once again, weak and strong sustainability paradigms collide. The former is represented by classical economics, while the latter is embedded into the Ecological Economics paradigm which presents an alternative to the classical one. Martinez-Alier and Munda will guide us during a brief introduction to this alternative approach.

As Martinez-Alier points out, ecological economists generally view the reliance on prices as primary expression of values with skepticism. They view economic activity as "taking place within a larger context of material flows, or *throughput* [5] which originate in the environment, are processed in economic activity and released back into the environment as high entropy waste" [18]. In turn, for classic economists, the environment is a place of conflict between competing values and interests, and different groups and communities that represent them. The different dimensions of value can conflict with each other and within themselves, and any decision will distribute different goods and bads across different groups both spatially and temporally.

From the weak sustainability side, several approaches have been proposed to cope with these conflicts. Most of them have their roots in Utilitarianism [19] and are based on the assumption of complete commensurability (substitutability without restrictions). The strong sustainability pole is well summarized by Munda's works which are very clarifying [20,21]. He focuses on causes and effects of commensurability and proposes interesting alternatives which accept a certain degree of commensurability that will be managed using soft-computing tools [22]. His proposal is in consonance with the "orchestration of science" proposed by Funtowicz and Ravetz in their post-normal-science paradigm [23] and by O'Hara's discursive ethics [24].

According to O'Hara, "it is not enough to ask how social and environmental functions can best be assigned monetary value so as to correct prices, what is needed instead is an understanding of the complex social, cultural, physical, biological and ecological system themselves. It demands relinquishing the centrality of the subsystem "monetary market exchange" and internalize economics into the material and non-material context of human lives and the environment" [24]. This proposal requires a methodology that allows the complexities of all systems to be explicitly admitted to

the valuation process rather than being implicitly considered in corrected market prices.

Eventually, one of the gaps in sustainability analysis has been identified: simple analytical approaches to sustainability cannot cope with its vast complexity. Besides, economic valuation presents some limitations which reveal the need for a complementary analysis which may be able to break the tough wall between the system (economics) and the environment (society and nature).

2.4. Energy sustainability. An exergetic thermodynamical approach

Bearing in mind the previous discussion on problems and limitations on sustainability assessments, and rescuing the primary objective of this research, that is, to assess the usefulness of exergy as an indicator of energy sustainability, it is time to summarize the path that led some pioneer researchers to propose exergy as a possible solution to energy sustainability studies.

Since concerns about energy sustainability issues rose to the top of the agenda of international institutions in the 1970s and 1980s, many contributions have been presented, most of them being based on particular sets of indicators [25–27,14]. By way of illustration, two studies are presented: firstly, Afgan proposes 4 sets of energy indicators regarding 4 different sectors: resources, economic, environmental and social. In that framework, the indicators within each sector are aggregated in order to provide a single figure regarding four different generation technologies: solar, wind, biomass and oil. These values represent a degree of sustainability according to a scale that was built during the aggregation process. Secondly, Vera's proposals guided the program by the International Atomic Energy Agency (IAEA) on indicators for sustainable energy development. This program involved two different phases. In the first one, 41 energy indicators were chosen [26] and were reduced to 30 in the second phase. They were divided into three groups according to the DSR framework: Indirect driving force, Direct driving force and State. As Vera emphasizes, this set is intended as a reference point or a basis upon which users can develop their own specific indicators. It means that further manipulation and aggregation of data would be needed.

Eventually, the main drawback of all the sets of energy sustainability indicators has been pointed out: all of them propose aggregations of *qualitatively* different concepts.¹ As was discussed above, aggregation appears as a critical problem inherent to the strategy of analyzing energy sustainability by using quantitative indicators. Even if mathematical consistency [17] is ensured in the process of aggregation, how could it be stated that a certain level of that aggregated figure objectively indicates the sustainable condition of the system under study? From a weak sustainability position, the answer to the previous question could be the following: it is just necessary to find a common measurement unit for all these indicators. Yet, from a strong sustainability perspective, the problem is even more difficult to solve given that total or partial substitutability among indicators is assumed in every aggregation, what is limited by this paradigm. In strong terms, finding a common measurement unit can solve the equation only if limits to aggregations are also set.

Traditionally, money has been the common measure proposed, but pure economic approaches are problematic, as explained above. Taking this matter into account, some researchers proposed a different approach based on thermodynamics. According to them, the relationship between society and the environment is not primarily economic but physical. Energy is not an economic transaction but a thermodynamic property. Hence, finding a way of introducing thermodynamics into the sustainable debate

became the final aim of an exhaustive work developed during the last 30 years.

Our attention will be placed here in thermodynamics. This discipline offers the basic knowledge needed to deepen into the roots of sustainability problems at a physical level. *Energy, heat, power, entropy* and *technical efficiency* are thermodynamic concepts whose clear definition is critical in order to offer accurate measures and guidelines for improving industrial processes as well as global energy policies. Within this broad world of thermodynamics, a powerful concept arose two centuries ago: *exergy*.

Since the second thermodynamic principle was formulated by Clausius in 1856 [28], a fruitful research has been developed in this area, and exergy has emerged as a crucial concept to be taken into account when trying to formulate the relationship between systems and their respective environments in thermodynamic terms. The research by Gibbs and followers was guided by a basic premise: energy did not properly reflect the elusive relationship between the system under study and its environment. The second law of thermodynamics (entropy) dictated that irreversibilities produce a continued degradation of energy. Exergy then emerged as the portion of energy which remained available after subtracting the effects of irreversibilities. Thus, exergy is the distilled result of a basic inquiry which is the available energy resulting from the interaction between natural and artificial systems with the environment they belong to. Thanks to this characteristic, some authors started to propose exergy as an alternative measurement unit which could substitute, or at least complement, classic economic approaches² to sustainability.

Unfortunately, Gibbs also acknowledged that uncertainties regarding the exergy calculation would never be fully analytically solved. Hence, the full potential of the inquiry which guided those researchers toward exergy, that is, a common measurement unit that could be the bridge between physics and economy, was not finished, for a pure thermodynamic approach would never be fully capable of covering it. Some other disciplines should offer their own achievements in order to complete the scene.

The roots of the necessary complementary work in sustainability are hidden behind this previous assertion. Broadly speaking, exergy appears as a powerful concept describing the sustainability issue in a double way: firstly, it can be proposed as that common physical measurement unit which can complement classic economic approaches under a weak sustainability paradigm. Secondly, exergy also condenses a very rich conceptual approach to sustainability by linking *systems* and *environment* in a single movement, and thus addressing also part of the strong sustainability concerns. Exergy refers to the available, or useful energy, but it is not a property of a material or process itself. It is the portion of energy which is susceptible to be used, i.e. transformed in work, *within a defined environment*. If the connection between the process and the environment is broken, the richness of the exergy concept disappears and becomes another chemical potential in which usefulness is limited to the efficiency improvement of certain industrial applications.

The next step will consist of precisely defining the exergy thermodynamic concept. This definition will clarify possible misuses and will focus our attention on its thermodynamic properties. Afterwards, different uses of exergy regarding sustainability studies will be presented and discussed, taking into account its precise thermodynamic definition as well as its rich conceptual power highlighted during the present introduction.

¹ For instance, the first indicator in the EISD set from the IAEA is the 'Total population', and the last one is the 'Rate of deforestation'.

² Although using exergy means a step forward in the way of dealing with global sustainability concerns, it is fair to acknowledge that it is barely capable of dealing with some dimensions of sustainability related to social issues, i.e. equity and wealth allocation, a limitation inherent to all the thermo-economical proposals. Hence, the contribution of exergy to sustainability assessments is normally restricted to the environmental pole.

3. Definition of exergy

3.1. Definition

Exergy is often confounded with energy. “Exergy is work, or ability of work, whereas energy is motion or ability of motion, not necessarily work” [29]. Exergy relates to the second law of thermodynamics and the works of Sadi Carnot who in 1824 stated: “the work that can be extracted of a heat engine is proportional to the temperature difference between the hot and the cold reservoir” [30]. Some years later, that famous quotation became the second principle of thermodynamics which was profusely debated and redefined during the next years. Gibbs was one of the prominent researchers in this area. He was also the conceptual father of exergy. In 1873, following a previous definition of *available energy*, he introduced the notion of *available work*: “We will first observe that an expression of the form

$$-\varepsilon + T\eta - Pv + M_1m_1 + M_2m_2 + \dots + M_nm_n \quad (1)$$

denotes the work obtainable by the formation (by a reversible process) of a body of which $\varepsilon, \eta, v, m_1, m_2, \dots, m_n$ are the energy, entropy, volume, and the quantities of the components respectively, within a medium having the pressure P , the temperature T , and the potentials M_1, M_2, \dots, M_n . (The medium is taken to be so large that its properties are not sensibly altered in any part by the formation of the body)” [31].

Gibbs' contribution was extremely important for thermodynamics theory. In fact, thermal optimization was conceptualized through his work.

However, several decades went by until the Slovenian Zoran Rant, at a scientific meeting in 1953, suggested that the term *exergy* should be used to denote *technical working capacity*, which is the natural evolution of Gibbs' *availability*. As Rant explained, energy literally means *internal work* from the Greek ‘en’ and ‘ergon’, and the prefix ‘ex’ implies instead an *external* quantity. By adopting this name, all previous expressions, such as *available energy*, *availability*, *available work*, *potential work*, *useful energy*, *potential entropy* and later introduced terms such as *essergy*, could in principle be abandoned. Nevertheless, in practice, it took 50 years for Rant's denomination to become accepted worldwide. A further description of this interesting historical evolution of the exergy concept, from the proposal made by Rant to its final consolidation, is included in [32]. It is noteworthy that this debate continued in the 60s, and led to the modern efficiency definitions we are using today.

Two modern definitions of exergy were proposed by Szargut [33] in the 80s:

- “Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above mentioned components of nature”.
- “Exergy is the shaft work or electrical energy necessary to produce a material in its specified state from materials

common in the environment in a reversible way, heat being exchanged only with the environment at temperature T_0 ”.

Similarly, Sciubba and Wall defined exergy as “the maximum theoretical useful work obtained if a system ‘S’ is brought into thermodynamic equilibrium with the environment by means of processes in which ‘S’ interacts only with this environment” [32].

It should be noted that, in all these definitions, the role of the environment in calculation of exergy is clearly highlighted. In order to obtain exergy, defining the system is not enough, a reference environment (RE) must be chosen. At the end of this section this important idea will be further explained.

Since, as mentioned before, exergy is commonly confounded with energy, some authors focused their academic contribution on resolving this conflict by clearly setting the difference between both concepts. Table 1 based on Dincer [34] shows these differences.

Before deepening into the thermodynamic roots of the exergy concept, it is worth mentioning the important role that *thermodynamic efficiency* plays in this debate. The total exergy value of a system is a worthless figure if not compared with other ones coming from a different system or that same system in a different situation (spatial or temporal). Efficiency will provide this information, yet obtaining that value is not trivial. The next section provides a short insight into this important issue.

3.2. Efficiency

Before presenting the different definitions of efficiency, it should be noted that efficiency improvement and sustainability are not synonymous. Improving the efficiency of thermal processes is always good news, but it does not ensure that sustainability goals are being met. Many other factors contribute to real sustainability that are not related with efficiency improvements.

Different formulations have been proposed for thermodynamic efficiency, opening a controversial debate among authors. Nevertheless, some degree of agreement has been achieved. According to Sciubba and Wall [32], the fruitful debate in the 60s converged to the following three definitions:

The Second Law or Exergy Efficiency

$$\varepsilon = \frac{\text{useful exergy output}}{\text{used exergy input}} \quad (2)$$

The degree of reversibility

$$\psi = \frac{\text{exergy of products}}{\sum(\text{used exergy input})} \quad (3)$$

The coefficient of exergetic destruction

$$\xi = \frac{\text{annihilated exergy}}{\text{total exergy input}} = \frac{T_0 \Delta S_{irr}}{\sum(\text{exergy inputs})} \quad (4)$$

Depending on the application under study, one or another efficiency definition will be used and some further derivations of them will be done. Cornelissen [35], in his Ph.D. thesis, included a

Table 1
Energy versus exergy.

Energy	Exergy
Dependent on the parameters of matter or energy flow only, and independent of the environment parameters	Dependent both on the parameters of matter or energy flow and on the environment parameters
Motion or ability to produce motion	Work or ability to produce work
Always conserved in a process, so can neither be destroyed or produced	Always conserved in a reversible process, but is always consumed in an irreversible process
In equilibrium with the ref. environment, its value is different from zero	In equilibrium with the ref. environment, its value is equal to zero

description of three different exergetic efficiencies, which are, nevertheless, formally equivalent to Wall's and Sciubba's proposals presented here.

3.3. Thermodynamic basis

Performing a complete derivation of exergy is out of the scope of this paper. Nevertheless, to introduce some basic concepts is absolutely necessary. It is worth mentioning the contribution made by Goran Wall who started an open tutorial divulgation project called *Exergetics* [36] intended for students and researchers interested in exergy. Besides, Dincer's contributions regarding the definition of the exergy concept from a thermodynamic point of view [34] are highly recommended because of their accuracy and rigour.

As mentioned in the introduction, although the exergy concept may go beyond its own technical definition, it was born into the Thermodynamic theory. Therefore, some basic notions must be highlighted in order to understand it properly. The First and Second Principles of thermodynamics are the milestones for any building which is to be constructed over it. Hence, a brief review of them is presented here:

First Principle of Thermodynamics: The internal energy of an isolated system is constant. [37]. A state function U called *internal energy* emerges from this principle. Since energy is never destroyed, its balance will always be achieved. A system S which is absorbing a certain amount of heat Q is producing work W and is changing from state 1 with kinetic energy E_{c1} and potential energy³ E_{p1} (affected by the gravitational field of the earth) to another state 2 with energies E_{c2} and E_{p2} , the energy balance equation which mathematically expresses the First Principle would be the following:

$$Q - W = \Delta U + \Delta E_p + \Delta E_c \quad (5)$$

Second Principle of Thermodynamics: "Heat cannot spontaneously flow from a colder location to a hotter location" (Carnot's formulation) [30]. Similar to the first principle, in which a state function called "internal energy" was defined, this second principle suggests the need to define a second state function which condenses this experimental verification. Entropy S was the chosen one. Its main property is the next: "entropy can always be created but never destroyed". The importance of this principle is such that Goran Wall dared to state [29] that "time and evolution are consequences of the second principle of thermodynamics".

The differential increment of entropy of a system S whose thermodynamic properties are fixed, and which is exchanging matter and energy with a defined environment, can be calculated applying the next formula:

$$dS = dS_e + dS_i \quad (6)$$

$$dS = \frac{\delta Q}{T} \quad (7)$$

$$dS_i \geq 0 \quad (8)$$

$$dS \geq \frac{\delta Q}{T} \quad (9)$$

where dS_e indicates *external entropy* and dS_i *internal entropy*.

As stated in Eq. (6), the balance equation of entropy cannot exclude the environment. This point is critical for our explanation, since the exergy concept will derive from it.

Reversibility and irreversibility are also crucial concepts related to this Second Principle. Reversible processes are theoretical abstractions in which there is no entropy generation dS_i at all. No pure reversible processes can be found in nature but it is a very useful concept in thermodynamics, since it establishes the maximum theoretical level of availability of energy in a system. The exergy concept will directly emerge from this abstraction. For further developments on this topic, Szargut's description of this phenomenon [33] is highly recommended because of its clarity and accuracy.

Once the first and the second principles of thermodynamics have been introduced, another step is required to obtain useful and complete expressions of exergy. Instead of proposing a general expression which normally implies a difficult physical interpretation, many authors divide this issue in two parts regarding the type of thermodynamic system under study, i.e. closed or open. In order to be faithful to our aim of clarity, this alternative was the chosen one.

3.4. Closed systems

A closed system can exchange heat and work but not matter with its surroundings. The available energy of a closed system S is defined as the maximum *useful work* obtainable when the system is brought from its initial state (T, p) to a death state (T_0, p_0) by means of reversible processes. It is important to notice that the final state here is not the *environmental state* but the *death state*. It implies that complete equilibrium (physical and chemical) has been reached. Since closed systems do not exchange matter with the surroundings, chemical exergy will be equal to free (Gibbs') enthalpy⁴ and no further derivations must be done. It will not be the case in open systems as will be described in the next section.

The main formulation for this *useful work* is the following:

$$W_u = (U_1 + p_0 V_1 - T_0 S_1) - (U_0 + p_0 V_0 - T_0 S_0) \quad (10)$$

If the function L (exergy without flow) is defined according to the next formula:

$$L \equiv U + p_0 V - T_0 S \quad (11)$$

Eq. (10) can be reformulated as

$$A = L - L_0 \quad (12)$$

where A is the *available energy* or *exergy* in a closed system.

Alternatively, the expression for the differential change in available energy in closed systems would be

$$dA = \left(1 - \frac{T_0}{T}\right) \delta Q - \delta W_u - T_0 dS_i \quad (13)$$

which is very useful in thermal optimization applications.

Hence, in reversible processes where no entropy is generated (or available energy destroyed),

$$dA_{max} = \left(1 - \frac{T_0}{T}\right) \delta Q - \delta W_u \quad (14)$$

and

$$dA_d = -T_0 \cdot dS_i \leq 0 \quad (15)$$

This is Gouy-Stodola's theorem for a closed system: "In a closed system, the available energy destroyed when the system is brought from its initial state to the state of equilibrium is equal

⁴ When a system changes from a well-defined initial state to a well-defined final state, the Gibbs' free energy equals the work exchanged by the system with its surroundings, minus the work of the pressure forces, during a reversible transformation of the system from the same initial state to the same final state: $G = U + p_0 V - T_0 S$.

³ Kinetic and potential energies are usually neglected in closed systems.

to the temperature of the environment times the entropy generated" [38].

3.5. Open systems

An open system in steady state can exchange heat, work and matter with its surroundings. In open systems in steady state a certain amount of matter crosses the boundaries of a system S , absorbs a specific heat (per unit of mass) q and performs an specific useful work w_u . Total specific work w will be obtained adding to the balance, the *work of flow* due to the displacement of the control surface A from A_1 to A_2 :

$$w = w_u + p_2 v_2 - p_1 v_1 \quad (16)$$

The change of total specific energy in the system would be

$$q = \left(u_2 + \frac{1}{2} c_2^2 + g z_2 \right) - \left(u_1 + \frac{1}{2} c_1^2 + g z_1 \right) + (w_u + p_2 v_2 - p_1 v_1) \quad (17)$$

hence

$$q - w_u = h_2 - h_1 + e_{c2} - e_{c1} + e_{p2} - e_{p1} \quad (18)$$

where h , e_c and e_p represent the specific enthalpy, kinetic energy and potential energy respectively. Enthalpy is a crucial thermodynamic state variable. It includes the internal energy of the system and the work of flow in an specific control volume. Therefore, Eq. (18) represents the First Principle for an open system in steady state.

The next step consists of deducing the equation for exergy from previous results. As stated before, exergy will be the maximum useful work obtainable when an open system S is brought from its initial state to a final state of equilibrium.⁵ In open systems, distinguishing between environmental and death state is relevant. In this section we will assume that the final state is the environmental one. Hence, only physical exergy is calculated here. This important distinction is discussed in Sections 3.6.1 and 3.6.2:

$$b \equiv W_{u,max} = h - h_0 + q_{rev} \quad (19)$$

where q_{rev} , if the reversible process is operated in two steps, i.e. adiabatic and isothermal, is equal to

$$q_{rev} = T_0(s_0 - s) \quad (20)$$

Hence, the final expression for b is

$$b = (h - T_0 s) - (h_0 - T_0 s_0) \quad (21)$$

Besides, the expression for the differential increment of exergy in an open system derived from the first and the second principle and the previous results takes the form

$$db = \left(1 - \frac{T_0}{T} \right) \delta q - \delta w_u - T_0 ds_i \quad (22)$$

A new expression of the Gouy-Stodola's theorem has been obtained here:

$$db_d = T_0 ds_i \quad (23)$$

where db_d is the differential exergy destruction in the open system described above.

So far, equations for exergy in closed and open systems have been obtained. Yet, taking a closer look at these equations, the existence of different contributions to the total exergy of a system is revealed. Dealing separately with these contributions can be very useful in order to achieve a better understanding of the exergy concept. The next section develops this topic.

3.6. Components of total exergy

According to Szargut [33] and Bejan⁶ [39], the exergy of a defined system can be divided into the following elements:

$$B = B_k + B_p + B_{ph} + B_{ch} \quad (24)$$

where B_k expresses the kinetic exergy, B_p the potential exergy, B_{ph} the physical exergy and B_{ch} the chemical exergy.

Some authors include two more components to exergy: electro-magnetic exergy and nuclear exergy. Hermann's contribution to this topic is relevant [40]. Nevertheless, a high degree of uncertainty is present in their derivation. Moreover, both components are usually neglected in thermal applications. Therefore, they will not be included in the present derivation.

Moreover, in most of the exergy formulations, kinetic exergy (equal to the kinetic energy when the velocity is considered relative to the surface of the earth) and potential exergy (equal to the potential energy when it is evaluated with respect to the average level of the surface of the earth) are normally neglected, for average values for environmental condition are assumed.

This way, only chemical and physical exergies are always relevant and their sum is usually called *thermal exergy*⁷

$$B_{th} = B_{ph} + B_{ch} \quad (25)$$

We will now describe more in detail these two components to understand them better. Many different derivations of exergy can be found in the technical literature. Unfortunately many of them present a problematic lack of clarity in the derivation process, which is added to the inherent complexity of thermodynamics. Montes et al.' contribution [42] was the one chosen because of its simplicity.

3.6.1. Physical exergy

Physical exergy (B_{ph}) is the work obtainable by taking the system through a reversible physical processes from its initial state temperature T and pressure p to the state determined by the temperature T_0 and the pressure p_0 of the environment. Some important cases will be analyzed: *incompressible substances*, *ideal gases* and *ideal mixtures*.

For *incompressible substances* (liquids and solids), the difference of enthalpies

$$\tilde{h} - \tilde{h}_0 = \int_{T_0}^T C_p(T) dT + \tilde{v}(p - p_0) \quad (26)$$

hence, applying this result to Eq. (21), the expression for total molar exergy

$$\tilde{b}_f = \int_{T_0}^T C_p(T) \left[1 - \frac{T_0}{T} \right] dT + \tilde{v}(p - p_0) \quad (27)$$

For *ideal gases*, the derivation is similar to the previous one. The value of \tilde{b}_f is

$$\tilde{b}_f = \int_{T_0}^T C_p(T) \left[1 - \frac{T_0}{T} \right] dT + RT^0 \ln \frac{p}{p_0} \quad (28)$$

For *ideal gases mixtures*,⁸ calculating the increment of entropy when separated gases are brought to the final mixture represents

⁶ Both authors divide exergy into the same elements, but the notation is different. Szargut uses B for exergy, whereas Bejan uses E . Since E is normally used for Energy, in order not to mislead the readers, Szargut's notation was chosen.

⁷ Different suggestions have been done for this separation among partial contributions to the total exergy of a system. Recently, a very interesting proposal by Simpson [41] suggests a distinction between *internal* and *external* exergies, as well as a detailed derivation of the physical and the chemical exergy of a system.

⁸ A mixture of gases or a solution is ideal when the following linear expression can be adopted for the chemical potential of each substance:

$$\mu_i = \mu_i^0 + RT^0 \ln x_i \quad (29)$$

⁵ Kinetic and potential energy will not be taken into account. In most applications their relative importance regarding the internal exergy is despicable.

a very interesting study. If S_m is the final entropy of the mixture in the state (T, p) and S_i is the entropy of each gas (T, p_i) before the mixture is obtained, we obtain the following expression:

$$S_m(T, p) = \sum_1^n n_i S_i(T, p_i) \quad (30)$$

If all the gases in the mixture are ideal gases, the differential increment of entropy of each gas would be

$$dS_i = S_i(T, p_i) - S_i(T, p) = -R \ln \frac{p_i}{p} \quad (31)$$

and adding all the contribution of the different gases, the total differential increment of entropy in the mixture would be⁹

$$dS = -R \sum_1^n n_i \ln x_i \quad (32)$$

where x_i represents the molar fraction of gas i in the mixture. Hence, the final equation for molar exergy would be

$$\tilde{b}_{mixture} = \sum_1^n x_i \tilde{b}_i^0 + RT^0 \sum_1^n x_i \ln x_i \quad (33)$$

where \tilde{b}_i^0 is the molar exergy of gas i at T^0 and p^0 , that is, respectively the temperature and the pressure of the final mixture. The first addend on the right side of the equation represents the contribution of each gas separately, and the second addend incorporates the effect of mixing and bringing them to the temperature T^0 and partial pressure x_i of the final state.

3.6.2. Chemical exergy

The chemical exergy of a mixture of substances is the maximum useful work obtainable when it is brought from the environmental state (T_o, p_o, μ_o) to the death state (T_o, p_{oo}, μ_{oo}) by means of reversible processes.¹⁰

Chemical exergy can also be defined as the minimum useful work needed to synthesize a compound and to bring it to the environmental state from the elements present in that same environment [44]. This second definition is very interesting from the point of view of thermal optimization.

An extensive literature can be found regarding chemical exergy [45–48]. However, since Szargut's [33] contribution has become the most accepted one, it was the one we chose for the present development.

In the death state, the following expression is verified:

$$\sum p_{ooi} = p_o \quad (34)$$

and

$$W_{u,r} = -\Delta G = \sum_i n_i \mu_{oi} - \sum_i n_i \mu_{ooi} = \sum_i n_i (\mu_{oi} - \mu_{ooi}) \quad (35)$$

where μ_{ooi} are the *standard chemical potentials* of each substance involved. As Baierlein brilliantly stated [49], comprehending the notion of Chemical Potential is not an easy task. Similar to other physical potentials, it represents a capacity to produce work inherent to a system, whose origin is not clearly known. In his paper, he offers three interesting characterizations of this elusive concept.

(footnote continued)

where μ_i^0 is the chemical potential of the substance i at the temperature T^0 and pressure p^0 of the mixture.

⁹ Dalton's law has been applied here:

$$\frac{p_i}{p} = \frac{n_i}{\sum n_i} = \frac{n_i}{n} = x_i \quad (36)$$

¹⁰ This process can be modeled by means of semi-permeable membranes. Szargut's model [33] has been profusely used, yet it has been widely criticized as well [43].

Moreover, previous results are only valid when all the constituents of the reaction are present in the reference environment (RE). If that is not the case, a further development must be done. Let us consider the next reference reaction for a X compound which does not belong to the RE:



where C_j and C_k are respectively co-reactives and products of the chemical reaction which are present in the RE.

The useful work obtainable in the previous reversible reaction at temperature T_o and pressure p_o of the environment is

$$\tilde{W}_{u,r} = -\Delta \tilde{g}_o \quad (38)$$

Next, it is necessary to add to Eq. (38) the work produced and consumed by the products and reactives (effluents and influents) of the reaction, respectively

$$\tilde{W}_{products} = \sum_k n_k (\mu_{ok} - \mu_{ook}) = \sum_k n_k \tilde{b}_{ok} \quad (39)$$

$$\tilde{W}_{reactives} = -\sum_j n_j (\mu_{oj} - \mu_{ooj}) = -\sum_j n_j \tilde{b}_{oj} \quad (40)$$

Hence, the exergy of the reaction of a compound X which is not present in the RE would be the following:

$$\tilde{b}_o(X) = -\Delta \tilde{g}_o - \sum_j n_j \tilde{b}_{oj} + \sum_k n_k \tilde{b}_{ok} \quad (41)$$

In case X belongs to the RE, taking Eq. (37) into account is not necessary, therefore, applying Eq. (36) to a single species we would obtain the expression for molar exergy of that specie X :

$$\tilde{b}_o(X) = \mu_o(X) - \mu_{oo}(X) \quad (42)$$

Although previous equations provide the theoretical framework for the calculation of chemical exergy of any mixture or single species, usually *standard exergy values* for common substances are used. These values have been profusely calculated and tabulated [37,33,50,51]. Since these standard chemical exergies are so widely used, some notes following Szargut and Morris [52–55] will be added regarding this important and practical issue.

Standard chemical exergy is related to the substance in the standard state at normal temperature and pressure ($T_n = 298.15$ K, $p_n = 101.325$ kPa) with the assumption that the conventional mean concentrations¹¹ or partial pressures species in the environment have been taken into account. Szargut's model for calculating this standard chemical exergy is clearly highlighted in Section 2.3.2 of [33].

According to Szargut, the calculation of the standard chemical exergy for every substance is usually inconvenient. It is sufficient to calculate it for some pure chemical elements having simple reference reactions. From these values, the following equation can be used for other chemical elements and for chemical compounds. Hence,

$$b_{ch}^0 = \Delta_f G^0 + \sum_{el} n_{el} b_{ch,el}^0 \quad (43)$$

where $\Delta_f G^0$ is the standard normal free exergy of formation; n_{el} is the number of moles in the compound under consideration and $b_{ch,el}^0$ is the standard chemical exergy of each element.

This equation is formally equivalent to Eq. (37) and can be used in an inverse mode to calculate the free normal exergy of a reversible reaction:

$$\Delta_f G^0 = \sum_k n_k b_{ch,k}^0 - \sum_i n_i b_{ch,i}^0 \quad (44)$$

¹¹ These values are widely tabulated in the bibliography, i.e. [37].

The contribution of the Exercoecology group to these calculations is noteworthy. They developed an online exergy calculator which is able to calculate standard chemical exergies of a vast database of compounds based on their reference species [56].

Finally, after revising an extensive literature regarding chemical exergy, it is fair to say that many difficulties and some inconsistencies have been found (we will deepen into this point in Section 5). Most of these problems are related to the different REs used. Undoubtedly, this is a critical point that needs further attention.

3.7. Reference environment

In previous sections, the calculation methods for physical and chemical exergies of closed and open systems have been introduced. As was mentioned in the introduction, talking about exergy implies defining a system under study and the reference environment (RE) where that system belongs and shares energy and/or matter with. If physical exergy is the only component of total exergy of interest, defining this RE is not very problematic, since just temperature and pressure (static or dynamically) must be fixed. Yet, when chemical exergy is relevant (for instance, when combustion processes of fuels are involved, what is quite common in thermal optimization applications), reference species and their concentrations must be fixed as well, and that is not a trivial task at all. As stated by Valero and Szargut [57], contributions to the determination of REs could be divided into two main groups: *partial* and *comprehensive* approaches.

Some authors such as Bosnjakovic [58] and Gaggioli [59] established that the RE should be defined according to the specific characteristics of the process analyzed (*partial approach*). This criterion is based on the fact that some ‘a priori’ possible evolutions of the system cannot be attained because of process limitations. Hence, only possibilities of evolution that the system can practically attain are to be analyzed. According to them, “the RE is not a ‘dead state’ anymore but a reference state directly related to the process under study. Therefore, there is no need for a comprehensive RE”.

However, if the proposal of the research is not only to improve the efficiency of certain industrial process but also to deal with global aims, i.e. studying climate change or determining the natural capital of earth, no ‘a priori’ process limitations can be set, for the resources can follow an uncertain evolution process toward the dead state. In this case, defining a *comprehensive* RE is required.

Among all the different comprehensive approaches to REs some differences may be found. Valero groups them in three sets: *Death state's Criterion* [53], *Chemical Equilibrium* [50] and *Abundance* [60]. Although each approach presents advantages and disadvantages, Szargut's proposal is the most extended. It is based upon the following principle: “among a group of reasonable abundant substances, the most stable will be chosen if they also comply with the *Earth similarity criterion*” [57].

It is worth mentioning that Gaudreau, in his Ph.D. dissertation [61], made a thorough review of the literature regarding REs. In fact, his criticism toward exergy as a global sustainability indicator comes from the apparent lack of accuracy of these RE definitions. In Section 5 this issue is addressed in depth.

4. Applications of exergy to the assessment of sustainability

Exergy has been extensively used in the technical literature for the optimization of industrial processes. Some of these areas where exergy have been successfully used are efficiency improvement in thermal and chemical processes, development of

designing tools for thermodynamic optimization, studies of material properties related to a pre-defined reference environment, improvement of thermodynamic cyclic applications (steam power cycles, gas turbine cycles, renewable energy cycles), heat exchangers, cryogenics, chemical processes and agricultural and biological system analysis. Some interesting reviews can be found in the literature where these applications of exergy are presented [32,62,63].

In summary, exergy is universally recognized as an optimization tool. Yet, the inquiry presented in this research is a more specific one: can exergy be properly used as a global energy sustainability indicator? In order to give a sound answer, different contributions to energy sustainability studies in which exergy already represents a key concept have been reviewed and are presented next. They are grouped in two sets based on two different systems of energy valuation: user and donor side.

4.1. User-side contributions

When energy is evaluated according to its usefulness to the end user, it belongs to a receiver (user) system of value [64]. In these approaches, exergy will become the common measurement unit enriching classic thermodynamic techniques, i.e. Life Cycle Analyses and Thermoeconomics, traditionally linked to weak sustainability studies.

4.1.1. Life Cycle Exergy Analysis

Environmentally oriented Life Cycle Analysis or Assessment (LCA) became a very popular technique in the last two decades to analyze environmental problems associated with the production, use and disposal or recycling of products [71]. From a sustainability point of view, Life Cycle Assessment is a methodological framework that has offered a new and more precise means to estimate the environmental impacts attributable to the life cycle of a product [72].

According to Gong and Wall, the main drawback of LCA is related to its multidimensional approach, which causes large problems when it comes to comparing different substances. In order to solve this problem, they proposed exergy as the common measure needed, and formally created a new LCA, the *Life Cycle Exergy Analysis* (LCEA).

LCEA has been widely used in the analysis of different kinds of supply systems. Following Wall's scheme, the exergy flow through a supply system, such as a power plant, consists of three separate stages. First, we have the *construction stage* where exergy is used to build a facility and put it into operation. During this time some exergy is spent and some is accumulated or stored in materials. Second, we have the *maintenance* of the system during time of operation, and finally the *clean up stage*. These time periods are analogous to the three steps of the life cycle of a product in a classic LCA.

The condition for sustainability in LCEA is expressed as

$$E_{pr} \geq E_{in} + E_{indirect} \quad (45)$$

where E_{pr} represents the produced exergy and E_{in} expresses the input exergy. As Wall emphasizes, only when E_{in} comes from a pure renewable source, the sustainable condition of the process can be ensured.

Another proposal of exergetic-LCA is due to Cornelissen and Hirs, the *Exergetic Life Cycle Analysis* (ELCA) [66]. It uses the same framework of the LCEA [73], but a different criterion, which is now the *life cycle irreversibility*, i.e. the exergy loss during the complete life cycle of the product [35]. In the ELCA it is shown where the losses of natural resources take place. According to their authors, with this information, better proposals for reducing the loss of natural resources can be obtained.

The differences between Wall's LCEA and Cornelissen's ELCA are not very relevant. They can be found in their respective level of aggregation. The level of the former is high, i.e. it directly aggregates all the exergetic contributions in every step, whereas the latter tends to disaggregate every exergetic contribution in the three different steps in order to highlight local irreversibilities. Nevertheless, both approaches share the main advantages and disadvantages of applying exergy to classic LCA. On the one hand, measuring all the inputs and outputs in exergetic terms makes possible to calculate the global efficiency of the process under study and to set some exergetic limits to certain activities (wastes). On the other hand, difficulties in setting a comprehensive reference environment along with uncertainties on the exergetic valuations, in particular of waste products, limit its applicability.

Finally, it is worth mentioning Valero's contribution to this area. He suggests that the traditional framework of LCA, *from-cradle-to-grave*, should be modified for *from-the-cradle-to-the-cradle*. According to Valero, to complete the calculation cycle it is necessary to calculate also the exergetic cost of replacement of materials which have been degraded throughout the life cycle of a product. He proposed to calculate that value also in exergetic terms. Therefore, the value of the total cost measured in units of exergy is called the exergoecological cost, the larger the exergoecological cost for a product or service, the more unsustainable it will be. Actually, the exergoecological cost is a derivation of the exergetic-cost-analysis studies developed by CIRCE during the last three decades, contributions which are rooted and linked to the works of Szargut [53], Bejan [39] and other researchers in exergy accounting and thermoeconomics.

4.1.2. Thermoeconomics

According to Valero, "Thermoeconomics is that science which explains the physical bases of the cost and which unites the cost with the physical processes in which the sacrifice of physical resources is located, causalised and quantified in terms of thermodynamic irreversibility" [67].

A vast literature can be found regarding this issue. The first idea of linking thermodynamics and costing was explored by Lotka [74] and Keenan [75] who clearly realized that entropic issues were to be taken into account in monetary cost considerations. Besides, the word Thermoeconomics was first used by Myron Tribus in his MIT lectures. Later contributions were mainly due to El-Sayed [76], Tribus and Evans [77], and especially to Gaggioli [78] in the US. At the beginning of the 60s, almost simultaneously and by independent investigators, the joint application of exergy analysis and engineering economics was presented under the name of *Exergoeconomics*. The basic idea of this method was to apply the usual procedures of Engineering Accounting linking the prices of components to their operating parameters and to their exergetic efficiency, and pricing not the unit mass, but the specific exergy content of a (material or energy) stream. Szargut proposed the *Cumulative Exergy Content* (CEC) [33] method as a first conceptualization of this strategy. More recently, Valero, Lozano and others developed a new formalization: *Exergoecology*, or the exergy cost of a product, that is, the quantity of exergy which is necessary in order to produce it once the limits of analysis have been fixed [79–84].

As was introduced in Section 2.3, this process of cost formation is problematic. Uncertainties devoted to non-linearities will never be fully covered by pure analytical calculations (this issue will be addressed in depth in the Section 5). Besides, CEC and Exergoecology share the same advantages and disadvantages of LCEA and ELCA approaches. Exergy is a valuable common measurement unit capable of unifying heterogeneous flows, but the difficulty in setting a comprehensive reference environment and to evaluate

waste impacts in exergy terms generates uncertainties about the results.

4.2. Donor-side contributions

Unlike the previous user-side approaches, in the donor-side ones the energy valuation is done through a hierarchy of aggregated (donated) levels [64]. These methods focus on the environmental performance of the system under study on the global scale, including not only direct energy inputs but also economic and work flows, all of them transformed and evaluated in exergetic units. Although an aggregation of different kinds of natural capitals is used by these methods, the role that the environment plays in them places these methods within the strong sustainability paradigm. Regardless of their drawbacks which will be highlighted below, it is worth noting the courage of these donor-side contributions and the fresh air they bring to the sustainability research arena in which the role of the environment has traditionally been relegated to a second place.

4.2.1. Emergy

Emergy is the most extended exergetic donor-side approach to sustainability. Citing Odum's words: "Emergy is the *available energy* of one kind (usually solar) that has to be used up directly and indirectly to make a product or service" [85–87].

According to Odum, since solar energy is the main energy input to the Earth, all other energies could be scaled to solar equivalents to obtain common units. Hence, other kinds of energy existing on the Earth can be derived from these main source through a *transformity*, which is the main concept in emergy analysis. Transformity, or Unit Emergy Value (UEV), is "the solar emergy required to make one joule of a service or product". Hence, the solar transformity of a product is equal to its solar emergy divided by its available energy (exergy):

$$M = T * E \quad (46)$$

where M is the emergy (measured in solar emergy joules seJ), T is the transformity and E is the available energy (exergy).

Emergy analysis introduces an energy basis for the quantification or valuation of ecosystems, goods and services. According to Odum, valuation methods in environmental and ecological economics estimate the value of ecosystem inputs in terms that have been defined anthropocentrically, while emergy tries to capture the ecocentric value. It attempts to assign the correct value to ecological and economic products and services based on a theory of energy flow in systems ecology and its relation to systems survival. A fundamental principle of emergy analysis is the *Maximum Empower Principle*. It states that "systems that will prevail in competition with others, develop the most useful work with inflowing emergy sources by reinforcing productive processes and overcoming limitations through system organization" [88].

Odum asserts that this principle should be able to determine which ecological and also which economic systems would survive over time and hence would contribute to the development of future systems. The maximum empower principle suggests that designing *adaptive* systems rather than *effective* ones should be the final aim of sustainable policies.

Emergy has encountered a lot of resistance and criticism within the scientific community. Below, some advantages and drawbacks of Odum's contribution will be presented. According to Hau [89], the most attractive characteristics of emergy analysis are

- It provides a bridge that connects economic and ecological systems. Since emergy can be quantified for any system, their economic and ecological aspects can be compared on an

objective basis that is independent of their monetary perception.

- It compensates for the inability of money to value non-market inputs in an objective manner. Therefore, emergy analysis provides an ecocentric valuation method, opposed to an anthropocentric/economics-based approach.
- It is scientifically sound and shares the rigour of thermodynamic methods.
- Its common unit allows all resources to be compared on a fair basis. Emergy analysis recognizes the different qualities of energy or abilities to do work.
- Emergy analysis provides a more holistic alternative to many existing methods for environmentally conscious decision making. Most existing methods ignore the crucial contribution of ecosystems to human well being.

Although it is not the only ecological approach, it is noteworthy that these features of emergy analysis are particularly impressive since emergy was developed many decades before the more recent engineering and corporate interest in sustainability.

The major criticisms of emergy analysis are shown below:

- *Emergy and economics*: According to Ayres [90], the emergy theory of value focuses on the supply side and ignores human preference and demand.
- *Maximum Empower Principle*: The criticism is centered in Odum's claims about the general applicability of this Principle to all systems.
- *Combining disparate time scales*: Accounting for solar inputs over geological time scales is problematic since it is difficult to know the total inputs and processes over such a long period.
- *Representing global energy flows in solar equivalents*: Ayres questions such conversion since there is no simple way to discover how much of any one form of energy might have been needed to produce another in the distant past.
- *Problems of quantification*: Some authors claim that emergy analysis has not considered the uncertainty in many of the numbers used to calculate the transformities.
- *Problems of allocation*: The method used for partitioning or allocating inputs between multiple outputs makes the emergy algebra quite challenging.

In summary, it is easy to see that the most important drawbacks shown are related to the calculation of transformities. Not surprisingly, exergy researchers are centering their efforts in refining and systematizing these calculations [91]. Odum's emergy was a groundbreaking proposal still needing further developments, which will be able to solve the uncertainties about its scientific soundness. An enthusiastic community of developers, led by Mark T. Brown from Florida, is working hard to bring emergy to the fore in global sustainability studies. Its complementary nature opens a very fruitful landscape of cooperation among different disciplines in order to obtain more accurate results. Nevertheless, as Hau emphasizes, the biggest challenge yet for emergy is to overcome some preconceived misunderstandings to legitimate it as a sound thermodynamic approach.

4.2.2. Ecological cumulative exergy consumption

Emergy is the most important donor-side exergetic application to sustainability studies, but it is not the only one. Hau and Bakshi [69] proposed an expansion of Szargut's CEC (described in Section 4.1.2), called *Ecological Cumulative Exergy Consumption* (ECEC). It starts with the basic premise that available energy (as used in emergy analysis) and exergy are equivalent when three conditions are satisfied: the analysis boundary for both methods is

identical, the allocation method is the same at each node and the same approach is used for combining the global energy inputs.

According to Hau and Bakshi, these conditions are usually easy to satisfy, which implies that emergy transformities of ecological goods and services can be used to readily include their contribution in CEC analysis. Therefore, if the ECEC framework is used, CEC studies would be greatly enriched by Odum's holistic model becoming not only a thermoeconomic approach but also a complete open framework for sustainability assessments referenced to solar emergy.

Since ECEC is a combination of CEC and emergy approaches, it shares all the advantages and disadvantages of these approaches already presented above.

4.2.3. Extended exergy accounting

A third exergetic donor-side approach to sustainability studies comes from Sciubba's studies. Extended Exergy Accounting is a method developed by him [92] in the 90s. As ECEC, this method is a standard exergy analysis in which Szargut's CEC (see Section 4.1.2) is enriched by additional exergy flows that represent the exergetic equivalents of the Capital, Labor and Environmental Remediation Production Factors.

EEA condenses some key features of the pre-existing theories and procedures described in previous sections:

- The time span of an EEA assessment covers the entire life of the facility and/or product, as it is based on life-cycle assessment methods (see Section 4.1.1) [66].
- In EEA, all the inputs that contribute to the formation of a product are accounted for on an exergetic basis. The basic input is a given set of raw materials, as in cumulative exergy analysis (see Section 4.1.2) [33].
- EEA, like thermoeconomics [67,39], uses exergy cost balances to quantify the value of every flow of matter and energy that interacts with the system under consideration (see Section 4.1.2).
- EEA assigns labor an intrinsic primary resource-based value depending on the local exergy resource flow, with a method in principle very similar to that proposed by emergy analysis (see Section 4.2.1) [68].

EEA is based on two fundamental assumptions. Firstly, the cumulative exergy content of any product is equal to the sum of the raw exergy of the original constituents that form the input to the production process plus a properly weighted sum of all the exergetic inputs into the process itself. And, secondly, labor, capital, and non-energy externalities can also be reformulated in terms of exergy. EEA proposes to assign to labor and to human services an exergetic value computed as the total (yearly averaged) exergetic resource input into a portion of society divided by the number of working hours generated therein.

Moreover, EEA proposes a new means of measuring environmental impact and even to set constraints to it. Sciubba criticizes conventional economics approaches to this complex issue. As was introduced in Section 2.3, there is a growing concern that the acknowledged shortcomings in the treatment of environmental problems by the conventional monetary theory of value stem from basic flaws in the value-assignment paradigm of the latter. Sciubba's proposal advocates a substantially different approach: it includes in the exergetic cost of a product the *environmental pollution avoidance cost*, calculated as the additional extended exergy expenditure that is required for bringing all environmental discharges down to a zero (or equilibrium) physical exergy level. Clearly, this approach is closely related with Valero's exergetic cost of replacement of materials [67] and with Cornelissen's abatement exergy of emissions [66] (see Sections 4.1.1 and 4.1.2). However, a strong controversy appears when we deepen into these

Table 2
Exergy applications to sustainability analyses.

Type	Origin	Exergy approach	Source
User-side	Life Cycle Analysis (LCA)	Life Cycle Exergy Analysis (LCEA)	[65]
		Exergetic Life Cycle Analysis (ELCA)	[66]
	Exergoeconomics	Cumulative Exergy Consumption (CEC)	[33]
Donor-side	Ecosystem ecology	Exergoecology	[67]
		Emergy	[68]
		Ecological Cumulative Exergy Consumption (ECEC)	[69]
		Extended Exergy Accounting (EEA)	[70]

Table 3
Summary of features of exergy applications to sustainability assessments.

Type	Origin	Method	Features
User-side (weak sustainability)	LCA	LCEA	Based on classic LCAs, oriented to designing sustainable (renewable) supply systems
		ELCA	LCA extended to determine the consumption and depletion of natural resources
	Thermoeconomics	CEC	First conceptualization of exergetic cost
		Exergoecology	Based on the calculation of the exergetic cost of replacement of materials (from-the-cradle-to-the-cradle)
Donor-side (strong sustainability)	Ecosystem ecology	Emergy	Provides an ecocentric valuation method based on the Maximum Empower Principle
		ECEC	Algorithmic method that extends classic CEC to include the contribution of ecosystems
		EEA	Classic CEC including exergetic fluxes equivalent to labor, capital and environmental damage remediation cost

approaches regarding the calculation of the environmental impact by means of non-conventional economics methods. Calculating the non-used exergy in effluents is possible, yet stating that all that exergy is potentially harmful is not evident at all. Once again, this important drawback of exergy applied to sustainability studies, already highlighted in LCEA and CEC applications, appears.

After revising these interesting applications of exergy proposed in the literature (summarized in Table 2), it may be concluded that exergy has already emerged as an alternative valuation method in sustainability studies. It makes an important contribution to sustainability assessments by intimately linking the system under study to the environment which supports our productive system, a key factor usually underestimated by classic approaches. Nevertheless, some drawbacks have also been highlighted. Therefore it is time to summarize the advantages and disadvantages in order to finally answer the question which opened this research: can exergy be considered as a comprehensive energy sustainability indicator?

5. Discussion

As was explained in the introduction, evaluating the appropriateness of exergy as a global energy sustainability indicator was our final aim. In the previous sections, the thermodynamic roots of exergy were presented as well as the main applications that have been proposed in the literature where exergy is used as an energy indicator (or a key tool) in a complex sustainability framework. They have been summarized in Table 3. Besides, some advantages as well as some limitations have already appeared, and they have been summarized in Table 4. In this section they are presented and discussed systematically.

Revising the advantages of using exergy as a user-side or a donor-side sustainable indicator summarized in Table 4, it is easy to acknowledge that all of them are rooted in two main characteristics of exergy:

1. Exergy links the system under study and the environment that supports its activity. Exergy cannot be defined if a reference environment is not chosen and justified. This way the dyad system-environment is transformed into the new study object

in exergetic sustainability analyses, thus avoiding the main drawbacks of traditional economic approaches to sustainability in which the environment plays a secondary role.

2. Exergy can be used as a common measurement unit susceptible to be aggregated in a single indicator, either using a user-side approach (see Section 4.1) or a donor-side one (see Section 4.2). Thus, all the flows present in a sustainability analysis can be measured or transformed in exergetic terms.

Regardless of the merits of exergy exposed above, the relevance of its drawbacks will decide the appropriateness or not of using exergy as an energy sustainability indicator, thus answering the question which guided this research. Nevertheless, at this point of the discussion it is worth splitting the question into two different lines. In Section 4 two different groups of exergy applications based on two different valuation methods were introduced: user and donor side. These two methods are closely linked to the weak and strong sustainability paradigms introduced in Section 2.1. In Table 4 all the drawbacks are included, indicating that they affect weak or strong exergy-based sustainability approaches. It is noteworthy that they are additives, that is, those applicable to LCEA and ELCA are also present in exergoecology and in donor-side applications, likewise, limitations of exergoecology are also present in emergy, ECEC and EEA. Let us give a brief insight into them, summarizing and separating them according to its weak or strong nature.

5.1. Limitations of using exergy as a weak sustainability indicator

1. *Problems with the reference environment:* As was mentioned in Section 3.7, some authors proposed to define comprehensive exergy reference environments in order to deal with extensive environmental problems by means of exergetic analysis. However, the requirements of an ideal reference environment can severely limit the applicability of exergy. By the way of example, it may be highlighted the inconsistency of using exergy to measure the waste impact of a system linked to an environment which has been defined infinitely large and subjected just to internally reversible processes. Hence, if no comprehensive reference environment could be defined, the

Table 4
Summary of advantages and limitations of exergy applications to sustainability assessments.

Type	Origin	Method	Advantages	Limitations
User-side (weak sustainability)	LCA	LCEA	Rigorous scientific soundness based on classic LCA All energy and material streams are measured in the same unit: exergy Native distinction between renewable and non-renewable resources Same as LCEA (+) More extensive inventory analysis Links physics with economy using exergy as the nexus Introduce a theory of cost formation based on exergy Sound algorithmic implementation	Attempt to characterize waste impact in exergy terms Attempt to characterize exergy of non-working resources Same as LCEA Problems in the standardization of the reference environment Uncertainties due to non-linear irreversibilities
	Thermoeconomics	CEC	Solid exergy calculation of capital of earth (standard reference environment) Introduction of "from-the-cradle-to-the-cradle" framework	Same as CEC
Donor-side (strong sustainability)	Ecosystem ecology	Energy	Provides a bridge that connects economic and ecological systems Use a common exergy-based unit which allows all flows (energy, monetary, labor) to be compared on a fair basis Scientifically sound and shares the rigour of thermodynamic methods	Focuses on the supply side and ignores human preference and demand Uncertainty in the calculation of transformities of non-energetic inputs (monetary and labor) into exergy units Difficulty in the definition of proper time scales in global sustainability assessments
		ECEC EEA	Same as Energy (+) Extends classic CEC to a global donor-side evaluation Same as Energy (+) Sound algorithmic extension of CEC focused on the role of environment in sustainability studies	Same as Energy Same as Energy (+) strong assumptions made in the calculation of the Conversion Factors

attempt to use exergy as the common unit in sustainability analyses could not succeed.

2. *Attempt to characterize exergy of non-working resources:* For work-producing resources such as fossil fuels or biomass, exergy is often an appropriate measure of how much work can be extracted from these resources. However, useful work is not a relevant characteristic of a mineral. This criticism is directed against all those attempts which try to characterize the mineral capital of Earth (see Section 4.1.2). According to Gaudreau, determining exergy and useful work based on the *concentration exergy* (as was proposed by Valero [44]) is "simply not realistic". If so, the use of exergy as an indicator of sustainability is very difficult given that, as discussed in the previous section, all proposals are based on exergy aggregations derived from various energy and non-energy inputs to the system-environment.
3. *Uncertainties due to non-linear irreversibilities:* The previous criticism was related to the very definition and calculation of exergy, which affected every attempt of using exergy in weak sustainability analyses. Now, the relation between exergy and cost is put under exam. Valero and coworkers have been analyzing these issues for decades. They have focused on the problem of the cost-formation and the role that exergy could play in that crucial debate. Some of these issues were introduced in Section 4.1.2. In a very interesting article [93], Valero describes the advantages and disadvantages of using exergy methods for cost allocating and accounting. In a fascinating search for Aristotelian causality in thermoeconomics terms, Valero states that irreversibility is the *causa efficiens* of cost. Eventually, Valero is proposing a global consensus for the exergy use. That consensus would imply the definition of a comprehensive standard reference environment which would objectively solve the problems related to chemical exergy derivations. If that consensus were obtained, exergy could be that universal link between physics and economy in a static scenario. But even if we agree in the fact that an static exergy evaluation of a system, calculated over a comprehensive standard reference environment, comprises the total complexity (causes) of irreversibility within natural and artificial processes, linearity is a hidden assumption that has not been put under exam. It may be assumed that linear causes of irreversibilities, i.e. causes that can be analytically predicted and measured, can be traced through exergy-cost evaluation, but non-linear causes still occur in nature which cannot be analytically calculated in exergetic terms.
4. *Attempt to characterize waste impact.* That is the aspiration of some of the exergy methods described in Section 4. For instance, Cornelissen's ELCA and Wall's LCEA (see Section 4.1.1) in the analysis of the clean-up process propose an exergetic method for the evaluation of the emissions. Besides, Valero and coworkers, in their from-the-cradle-to-the-cradle LCA proposal (see Section 4.1.2), quantify the footprint that mankind imposes on Earth based on its exergy cost. Gaudreau emphasizes the lack of agreement among researchers in this point [43,61]. According to him, although several attempts have been presented, there is no empirical evidence that there is a direct correlation between the amount of exergy present in the wastes of a process and the potential harm that this exergy is able to inflict to the environment, a basic calculation in sustainability studies applied to regions and nations.

5.2. Limitations of using exergy as a strong sustainability indicator

As was indicated above, the drawbacks included in Table 4 are additive. Hence, the strong sustainability (donor-side) approaches

described in Section 4, share the same drawbacks explained above plus a new one related to the calculation of transformities in energy, ECEC and EEA methods. These values are used to transform not only energetic and material inputs but also monetary and labor flows into the system under study. Strong assumptions are made during the calculation process of transformities which affects the accuracy of the sustainability analyses in different ways [90].

6. Conclusion

Along the previous sections, exergy has been defined and examined in the different uses proposed in the vast existing literature regarding the assessment of sustainability. As was emphasized in these sections, exergy inextricably links the system and its environment, as well as unifies different measures (materials, funds, processes, etc.) constituting a single weak or strong figure which can be easily measurable and comparable. The strength of exergy relies on these relevant characteristics. Yet, at the same time, its main drawbacks are related to these same features, i.e., problems in the exergy evaluation, in the non-linear thermodynamic cost-value formation process and in the calculation of transformities.

Therefore, the question is still open: what can exergy offer to this global framework? Will it just be a useful tool for thermal optimization of industrial processes as stated by Gaudreau [43]? Could we use it as a reliable thermoeconomic variable in charge of measuring irreversibilities, as argued by Valero (see Section 4.1.2)? Could exergy be used as a donor-side measurement of the memory of energy present in any product, as Odum states (see Section 4.2.1)? In short, could exergy be used as an overall weak sustainability indicator? And, are strong exergy-based sustainability approaches scientifically sound?

Regarding the first question, different weak sustainability approaches in which exergy is a key element have been analyzed. All of them are widely used and accepted by the scientific community. Problems in the calculation of exergy really exist, especially those related to the calculation of waste impact in exergy terms, but this limitation is also present in non-thermodynamic sustainability approaches. Therefore, there is no doubt that exergetic LCAs and exergoecological studies will still offer a valuable contribution for sustainability assessments.

Strong exergy-based sustainability studies have important drawbacks, as has been clearly highlighted above, yet this limitation is not a resigned acceptance of uncertainty. The accuracy of the reference environment used will define the accuracy of the global sustainability analysis. We are not referring only to the definition of the bio-physical environment, but also to the social and the economic environment, which is needed to calculate the transformities in strong sustainability approaches. Proposals like Energy, ECEC and EEA, regardless of their limitations highlighted in Section 4, are partially successful in their attempt to offer alternative (complementary) sustainability studies based on second law of thermodynamics. These donor-side holistic approaches to sustainability studies are rooted over this conviction: exergy is not only a static thermodynamic indicator but also an open door to a new way of counting with the environment. Gaudreau's criticism regarding the inability of exergetic methods to accurately measure the environmental impact of human activity is relevant, yet the objective of these methods is not that pretentious. Energy as well as ECEC and EEA analyses, although will never reach a deterministic result regarding the global sustainable situation of a pair system-environment, will rather offer an alternative thermodynamic insight into them. Another issue has to do with the uncertainties in the calculation of transformities, which have cast a lot of doubts among classic sustainability researchers.

Nevertheless, as Hau highlights [89], some of these doubts come from very extended misunderstandings. The community of researchers around energy and other approaches is continuously increasing and offering new sound improvements in the calculation of transformities that increase our confidence in the capacity of these approaches to occupy an important role in future sustainability studies.

From the authors' point of view, these strong approaches can play a key role in a sustainability framework designed in order to obtain sustainable policies which are able to maintain homeostatic¹² relations between the system under study and its environment, thus complementing traditional economic approaches which are mainly focused on the economic and social poles of sustainability. This way, exergy can be not only a static *weak* indicator of the efficiency of a system but also a *strong* conceptual tool to be taken into account in the very definition of the framework. Since exergy relates environment and systems, using it into sustainability studies forces the researcher to define not only the system under study but also the environment in which it operates. This is a critical point. Once the boundaries of the system are accurately set, the limitations of the research are set as well.

Moreover, exergy may teach us an important lesson regarding the transdisciplinarity condition of sustainability studies. As has been highlighted, the nature of the relationship between system and environment is intrinsically undetermined. This does not mean that partial analytical approaches cannot be proposed, they are absolutely necessary indeed, but they cannot cope with the uncertainties inherent to its irreducible relationship.¹³ Therefore, as stated by Munda [20], since no pure analytical solution for this issue will be found, a wider framework is to be adopted including social and ethical thinking. By deepening into its complementary system-environment nature, ethics and social thinking find in the exergy concept an open door to a collaborative effort along with physics. Thus, the circularity of the proposal is clearly established: from physics to ethics, and vice versa (Max-Neef's transdisciplinarity paradigm appears in our sustainable landscape [96]).

Sustainability is a complex issue. No matter how sophisticated linearities we invent, they cannot cope with its elusive condition. Hence, *complementary* (in Bohr's sense¹⁴) contributions coming from different fields are all welcome and can constitute a trans-disciplinary effort which will offer a new insight into *real* problems regarding our limited, fascinating *real* world. Within that framework, exergy is already providing a valuable contribution in a double way: from a weak sustainability point of view, by offering solid thermodynamic insights into sustainability issues, and from a strong sustainability perspective, by formally reminding that system and environment, i.e. humankind and earth, are inextricably linked.

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¹² Homeostasis is the property of a system that regulates its internal environment and tends to maintain a stable, constant condition [95].

¹³ A very interesting discussion regarding reductionism, uncertainties and bounded rationality can be found in [97,98].

¹⁴ "Only the totality of the phenomena exhausts the possible information about the objects" [99].

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